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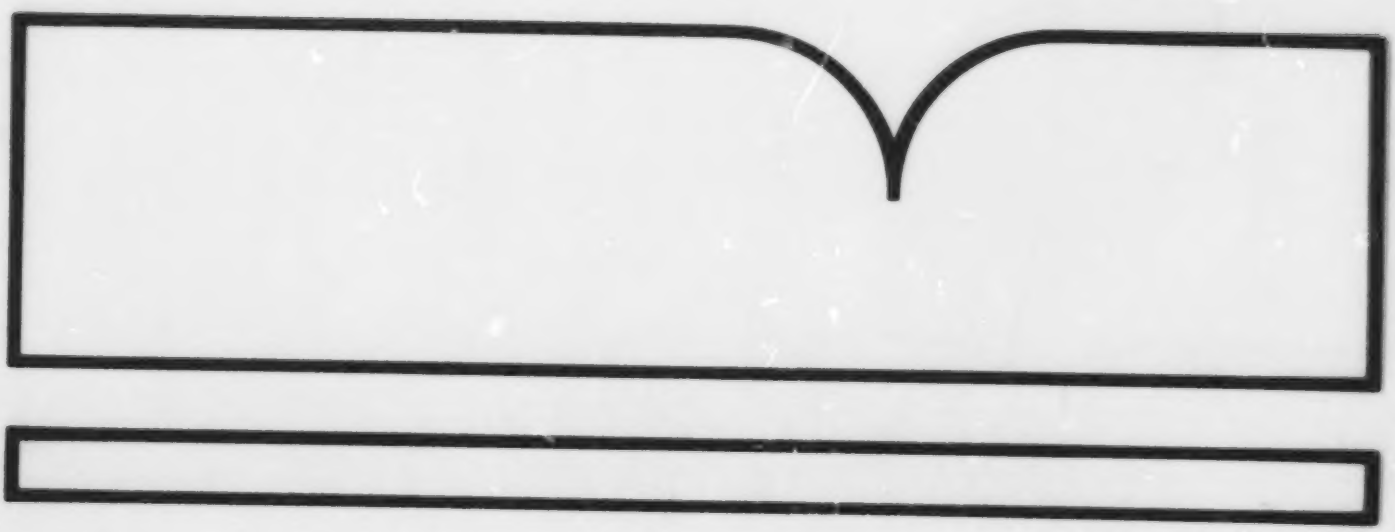

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Structure of the Planetary Boundary Layer and Implications for its Modeling

JOHN C. WYNGAARD

National Center for Atmospheric Research, Boulder, CO 80307*

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ABSTRACT

Through the innovative use of laboratory experiments, numerical simulations, and direct measurements, researchers have greatly extended our knowledge of planetary boundary layer (PBL) structure over the last 15 years. This paper reviews some recent findings as they bear on the modeling of both convective and stable PBLs.

While recent reviews indicate that some PBL models used in air quality applications reflect little of our current understanding, there is also encouraging evidence that updating these models can be straightforward and rewarding. The time seems ripe for the development of a new generation of PBL models, and some issues involved in their optimum design are discussed.

1. Introduction

Although the air quality modeling community is potentially a major user of planetary boundary layer (PBL) parameterizations, there is increasing concern that contemporary diffusion models do not reflect our current understanding. In a recent review, Smith (1984) relayed specific criticisms of ten rural diffusion models, for example, and concluded that none is up-to-date scientifically. Weil (1983) has shown how such models can be improved, however, and perhaps before long we will begin to see a new generation of diffusion models that do use more of our current understanding of PBL structure.

This understanding increased greatly during the information explosion of the 1970s when researchers largely completed studies of the surface layer and began extensive probing of the entire depth of the PBL. Much of this new knowledge is already available to the user community; for example, the new Panofsky–Dutton (1984) text treats the surface layer in detail unknown when the Lumley–Panofsky monograph was published in 1964.

The activity of the 1970s has also given us valuable new ways of studying the boundary layer. While traditional measurement techniques are less attractive for today's larger-scale problems than they were for the earlier surface-layer studies, due to the expense of obtaining the vast data bases required for reliable statistics, it seems that remote sensing, large-eddy simulation, and laboratory experiments can provide some of the data needed for progress. Thus, PBL researchers have continuing opportuniies to provide simple and realistic parameterizations to the broad user community. It seems that using these in improved PBL and diffusion models remains largely a challenge for the future, however.

Another influence on my perspective has been the broad, historical reviews of PBL structure in the Nieuwstadt-Van Dop (1982) and Panofsky–Dutton (1984) monographs. Thus, the discussion here will focus on some new insights into the structure of the PBL and on directions for future PBL research and modeling, considering both the needs of the air quality and PBL modeling communities and the new tools available to PBL researchers today.

2. Conceptual models of structure and physics

a. Convective PBL

Figure 1 shows a three-layer model (Deardorff, 1979), which is a convenient framework for discussing the ensemble-averaged structure of the convective PBL. This has a surface layer, a mixed layer (not always an accurate descriptor!), and an interfacial layer.

Figure 2 is an artist's representation of the unaveraged, local structure of the convective PBL. The height of its inversion "lid" varies in space and time due to the large convective eddies below and the wave motions in the stably stratified air above. Averaging over an ensemble of realizations (or over time in stationary situations, or over horizontal planes in homogeneous situations) transforms this lid into the smooth, rather thick interfacial layer shown in Fig. 1.

The convective PBL typically evolves in time and sometimes in the horizontal as well. Often we can assume it is in a state of "moving equilibrium" during this evolution. That is, even though its gross parameters (e.g., surface fluxes, height) are changing, its structural

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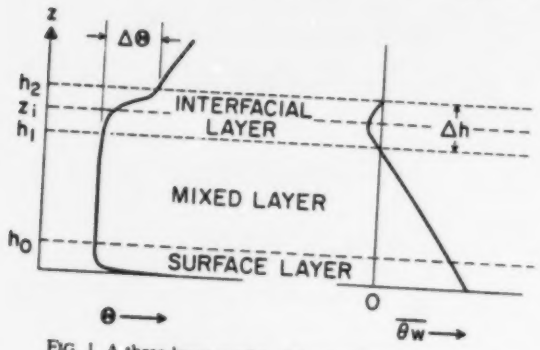

FIG. 1. A three-layer model of the averaged structure of the convective PBL (after Deardorff, 1979).

relationships can be taken to be those of a steady state, horizontally homogeneous case. This assumption is thought to be valid if the turbulence time scale (z_i/w_*, where z_i is the PBL depth and w_* the convective velocity scale) is much less than the time scale of the changing boundary conditions, or the time scale for changes in the moving frame, in the case of inhomogeneity. This should often be the case, since this turbulence time scale typically ranges from 200 to 2000 s.

Of these three layers in Fig. 1 the surface layer is the most easily measured and, hence, the best understood, thanks to Monin–Obukhov (M–O) similarity (Busch, 1973; Panofsky and Dutton, 1984). This scheme, while very successful, is not as complete a description as we perhaps once thought. For example, we now know that mixed-layer turbulence influences statistics of horizontal velocity near the surface (Panofsky *et al.*, 1977). Businger (1973) and Caughey and Wyngaard (1979) suggested that this could also cause the surface roughness to influence surface-layer structure. The hypothesis is that the large convective eddies induce local mean winds of random orientation and speed w_* near the surface. These, in turn, produce turbulent kinetic energy through the interaction of their wind shear and Reynolds stress, the latter depending on the surface roughness. Hence, we suspect that surface roughness could also influence surface-layer structure. Neither of these effects is allowed in the M–O similarity hypothesis.

If we define the surface layer in the usual way, i.e., as that depth over which the turbulent flux varies little (10%, say) from its surface value, then because the slope of the flux profile is so variable we must accept different surface-layer depths for different quantities. For example, let the turbulent flux profile vary linearly between F_s at the surface and RF_s at mixed-layer top (z_i). Then, one finds the surface-layer depth h_0 to be

$$\frac{h_0}{z_i} = \frac{0.1}{|(R-1)|}. \tag{2.1}$$

Typically, R is fairly small for temperature (approximately 0.2) but is larger for water vapor (~0.5–1.0; Wyngaard *et al.*, 1978), and can be even larger for momentum (Deardorff, 1973). In principle, circumstances might arise in which R could be very large for trace constituents with a small deposition velocity, and hence surface flux, but with a large, entrainment-induced top flux (Slinn, 1983). In such cases, the effective surface layer could be only 1 m deep!

Given our experience with turbulent transfer in other flows (Tennekes and Lumley, 1972), we would expect the eddy diffusivity in midregions of the convective PBL to be of order $0.1 w_* z_i$. This is typically large enough in clear weather over land to give vigorous vertical exchange, leading to the common term "mixed layer." Its convectively driven turbulence seems to fill the space available, even penetrating into the surface and interfacial layers, and the evidence suggests that for $-z_i/L$ values greater than 5 or so, the PBL reaches a convective state in which (to a first approximation) its shear-produced turbulence can be ignored. This

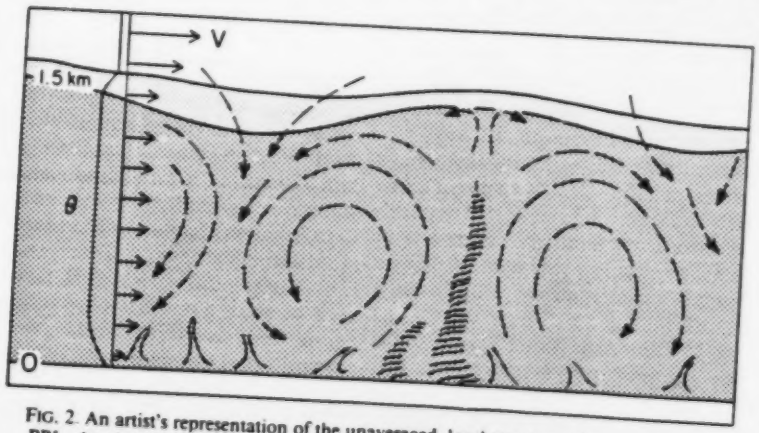

FIG. 2. An artist's representation of the unaveraged, local structure of the convective PBL, showing its large, convective eddies, plumes, and the sharp capping inversion.

might be surprising, because a simple calculation (Wyngaard, 1983) indicates that at $-z_i/L = 5$ the layer-averaged shear-production rate still exceeds the buoyant production rate by a factor of 3!

The simplest framework for the structure of the midregions of the convective PBL is mixed-layer similarity. Its governing parameters are the surface temperature flux Q_0, the buoyancy parameter g/T mixed-layer depth z_i, and scalar surface flux $\overline{cw}_s$. Caughey (1982) has surveyed its applications to data from several field programs.

The limitations of mixed-layer similarity are more severe than those of M–O similarity; perhaps most critical is its inability to account for the influence of interfacial-layer processes on mixed-layer turbulence. This can be important in the transport of scalar species. For example, the entrainment of dry air aloft into a moist convective PBL can generate large humidity fluctuations, even near the surface (Deardorff, 1974b; Wyngaard and LeMone, 1980; Caughey, 1982; Guillemet *et al.*, 1983). Accounting for this is beyond the scope of both the M–O and the mixed-layer similarity hypotheses.

Carruthers and Hunt (1984) used a linearized wave calculation to argue that the turbulent kinetic energy transfer between the mixed layer and the interfacial layer depends on the "stiffness" of the capping inversion; this transfer occurs via the pressure-vertical velocity covariance, and they argue that it influences the profile of the vertical velocity variance. Again, this cannot be treated within the mixed-layer similarity framework.

Moeng and Wyngaard (1984) have proposed an improved mixed-layer similarity hypothesis for conservative scalar statistics; it includes the scalar flux at mixed-layer top ($\overline{cw}_i$) as a governing parameter. The scalar variance profile, for example, is then predicted to be

$$\overline{c^2} = \left(\frac{\overline{cw}_s}{w_*}\right)^2 f_b + \left(\frac{\overline{cw}_i}{w_*}\right)^2 f_t + 2\,\frac{\overline{cw}_i\,\overline{cw}_s}{w_*^2} f_{tb}, \quad (2.2)$$

where f_b, f_t, and f_{tb} are functions of z/z_i. The first term represents the contribution from the surface flux, the second the contribution from the entrainment flux, and the third is a joint contribution. Only the first term is included in the conventional mixed-layer similarity. Their simulation results (Fig. 3) confirm that the second and third terms in (2.2) can be quite important.

While the idealization of well-mixed mean wind, temperature, and mixing ratio profiles does have its roots in observations, there are also many unmixed examples in the literature (e.g., Mahrt, 1976; Lenschow *et al.*, 1980; Klapisz and Weill, 1982). Figure 4 shows an unmixed example from a baroclinic PBL. The rawinsonde profiles were measured at the Boulder At-

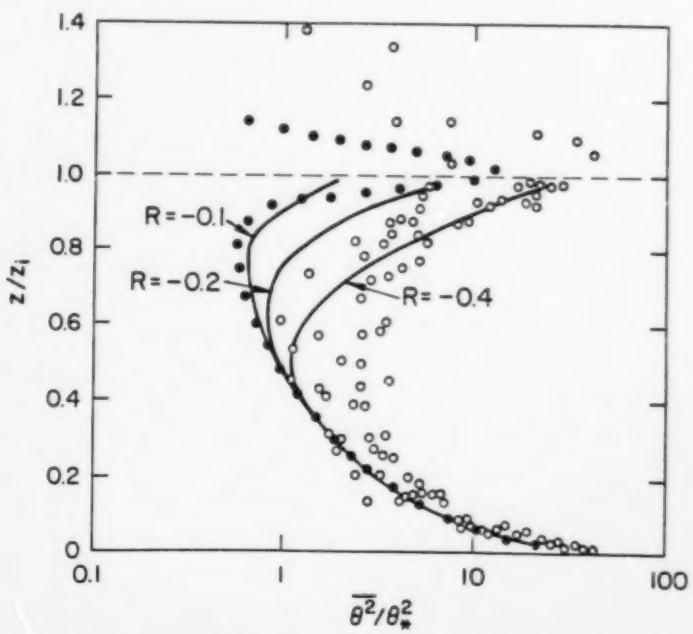

FIG. 3. Temperature variance profiles in the convective PBL, made dimensionless with $\theta_* = Q_0/w_*$. The solid lines are the Moeng–Wyngaard (1984) parameterization for various values of $R = \overline{\theta w}_i/\overline{\theta w}_s$. Open circles are data from Caughey and Palmer (1979; $-0.4 < R < -0.1$); dots are laboratory data from Willis and Deardorff (1974; $R = -0.23$).

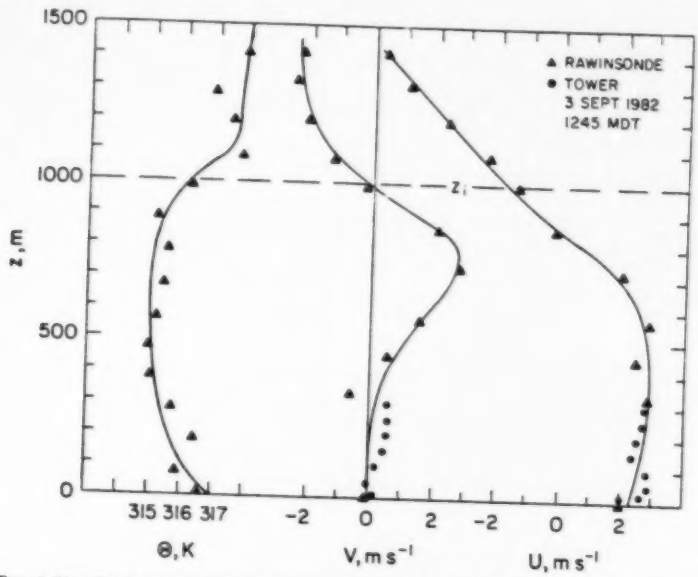

FIG. 4. Unmixed wind profiles from a baroclinic convective PBL with $-z_i/L \approx 250$, measured during diffusion experiments at the Boulder Atmospheric Observatory.

mospheric Observatory during some diffusion experiments in September, 1982 (Wilczak, personal communication, 1984). The height of the inversion base, z_i, was about 1000 m, and the synoptic flow aloft was westerly. The near-surface flow, driven by the heating over the sloping terrain, was easterly. Note that there was considerable wind shear in the upper half of the PBL, even though conditions were very convective ($-z_i/L \approx 250$).

Unfortunately there is no effective similarity theory for mean profiles in the mixed layer. Thus, let us begin by examining the mean conservation equations to see when the mean profiles might be expected to be well-mixed. Consider first the mean profile of a passive, conservative scalar constituent C whose mean conservation equation is

$$\frac{\partial C}{\partial t} + A(z) + W\frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\overline{cw} = 0, \qquad (2.3)$$

where $A(z)$ represents mean horizontal advection. Differentiating with respect to z gives the "mean gradient budget":

$$\frac{\partial}{\partial t}\left(\frac{\partial C}{\partial z}\right) = -\frac{\partial A}{\partial z} - \frac{\partial}{\partial z}\left(W\frac{\partial C}{\partial z}\right) - \frac{\partial^2}{\partial z^2}\overline{cw}. \qquad (2.4)$$

If the mean gradient is independent of time, the right side of (2.4) vanishes. Of course, this does not imply that the individual terms on the right side vanish, but if they are small we might expect that a well-mixed layer could exist, given sufficient convectively driven turbulence.

Using (2.4) requires a closure approximation for the turbulent flux term, and this remains an active and controversial area. For our brief survey discussion here I will use a variant of the eddy-diffusivity closure common in high-resolution PBL models (Blackadar, 1979), but this is known to have inadequacies in convective turbulence (Turner, 1973; Wyngaard, 1984a). With that caveat, then, let us use (2.4) to investigate the mean profile.

If the mean advection and time-change terms in (2.4) are negligible, then the flux profile approaches the linear form

$$\overline{cw} = \overline{cw}_s(1 - z/z_i) + \overline{cw}_i(z/z_i). \qquad (2.5)$$

Wyngaard and Brost (1984) have argued that in this case the mean gradient can be parameterized as

$$\frac{\partial C}{\partial z} = -\frac{\overline{cw}_s}{w_* z_i} g_b - \frac{\overline{cw}_i}{w_* z_i} g_t, \qquad (2.6)$$

where g_b and g_t, the "bottom-up" and "top-down" gradient functions described in detail by Moeng and Wyngaard (1984), depend on z/z_i.

The change in C across the mixed layer in this simplest case is found by integrating (2.6); this "equilibrium" change is (Wyngaard, 1984)

$$\Delta C_e \equiv (C_1 - C_0)_e = -\frac{\overline{cw}_s}{w_*}\Delta_b - \frac{\overline{cw}_i}{w_*}\Delta_t, \qquad (2.7)$$

where Δ_b and Δ_t, both positive, depend on z_i/L, the interfacial-layer thickness, and w_e/w_*. In the case of temperature the two contributions on the right side of (2.7) tend to balance, since the two fluxes are of opposite sign. For scalars such as humidity, however, the contributions add since the fluxes have the same sign, and as a result their profiles tend to be less well-mixed.

We can derive an equation for $\Delta C = C_1 - C_0$ in the general case by integrating (2.4) across the mixed layer, or, equivalently, by evaluating (2.3) at h_1 and h_0 and subtracting. The resulting equation is

$$\frac{\partial}{\partial t}\Delta C = w_e \left.\frac{\partial C}{\partial z}\right|_{h_1} - \Delta A + \left.\frac{\partial}{\partial z}\overline{cw}\right|_{h_0} - \left.\frac{\partial}{\partial z}\overline{cw}\right|_{h_1}, \quad (2.8)$$

where $w_e = (\partial h_1/\partial t) - W(h_1)$ is the entrainment velocity at h_1 and ΔA is the change in horizontal advection across the mixed layer.

If the time-change and differential advection terms in (2.8) are small, the entrainment and flux-divergence effects are in balance:

$$w_e \left.\frac{\partial C}{\partial z}\right|_{h_1} = \left.\frac{\partial}{\partial z}\overline{cw}\right|_{h_1} - \left.\frac{\partial}{\partial z}\overline{cw}\right|_{h_0}. \quad (2.9)$$

If our scalar is potential temperature with the profile in Fig. 1, then the mean advection term in (2.9) is positive; thus, the flux divergence must be more negative at the bottom than at the top. Figure 5, which is a collection of temperature flux data from Caughey (1982), bears this out through its curved flux profile.

The time-change and differential advection terms in (2.4) can also curve the flux profile. Assume that they are independent of z, so the flux profile is parabolic:

$$\overline{cw} = \overline{cw}_s(1 - z/z_i) + \overline{cw}_i z/z_i + 4\delta F z/z_i(1 - z/z_i), \quad (2.10)$$

where δF is the midlayer departure of scalar flux from a linear profile. Thus, (2.8) becomes

$$\frac{\partial}{\partial t}\Delta C = w_e \left.\frac{\partial C}{\partial z}\right|_{h_1} - \Delta A + \frac{8\delta F}{z_i}. \quad (2.11)$$

We might expect the flux departure to be proportional to a departure in the mean gradient, which suggests the parameterization

$$\delta F = -\frac{K}{z_i}(\Delta C - \Delta C_e), \quad (2.12)$$

where K is a turbulent diffusivity. In general, the flux profile is not parabolic, since the sources of curvature in (2.4) depend on z. Nonetheless, let us use the parameterization (2.11, 2.12). We then can rewrite (2.8) as

$$\frac{\partial}{\partial t}(\Delta C - \Delta C_e) + \frac{8K}{z_i^2}(\Delta C - \Delta C_e) = w_e \left.\frac{\partial C}{\partial z}\right|_{h_1} - \Delta A - \frac{\partial}{\partial t}\Delta C_e. \quad (2.13)$$

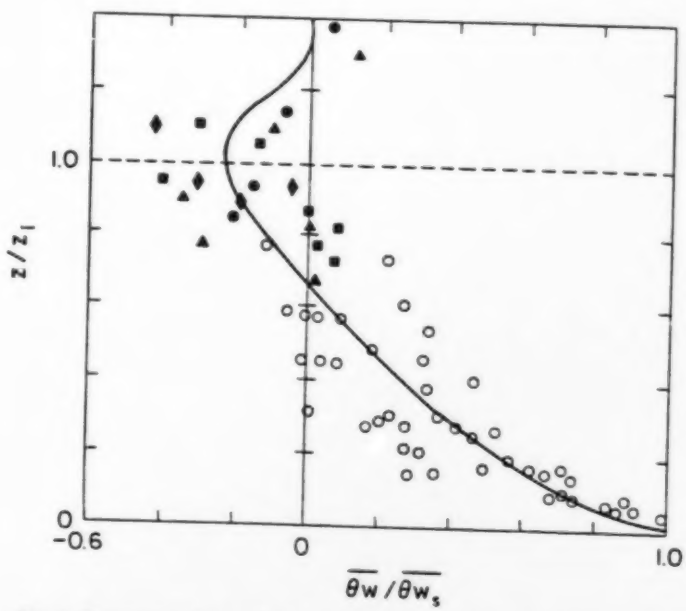

FIG. 5. Temperature flux profiles in the convective PBL, from data collected by Caughey (1982). The curve is fit by eye; note that its slopes at the surface and z_i are different, presumably due to entrainment effects [Eq. (2.9)].

The forcing terms on the right side of (2.13) suggest that entrainment, time changes in ΔC_e (through changes in z_i, w_*, or the top or bottom scalar fluxes) and differential advection can cause ΔC to depart from its equilibrium value. If conditions are quasi-steady [i.e., if the time-change term on the left side of (2.13) can be neglected], the solution is

$$\Delta C = \Delta C_e + \frac{z_i^2}{8\kappa}\left[w_e \frac{\partial C}{\partial z}\bigg|_{h_1} - \Delta A - \frac{\partial}{\partial t}\Delta C_e\right], \quad (2.14)$$

which suggests how the equilibrium change in C across the mixed layer can be augmented by these other effects.

If we go through the same process for mean horizontal momentum, we find that the equation corresponding to (2.11) is

$$\frac{\partial}{\partial t}\Delta\tilde{W} = w_e \frac{\partial \tilde{W}}{\partial z}\bigg|_{h_1} - \Delta\tilde{A} + 8\frac{\delta\tilde{\tau}}{z_i} - if(\Delta\tilde{W} - \Delta\tilde{W}_g), \quad (2.15)$$

in complex notation where

$$\Delta\tilde{W} = \Delta U + i\Delta V, \quad \Delta\tilde{\tau} = \Delta\overline{uw} + i\Delta\overline{vw},$$

$$\Delta\tilde{W}_g = \Delta U_g + i\Delta V_g,$$

$\Delta\tilde{A}$ is the complex differential advection, and the other notation is standard. An important forcing term in (2.15) is the change in geostrophic wind across the mixed layer, which from the thermal wind equation is

$$\Delta\tilde{W}_g = \frac{g}{fT} z_i\left(-\frac{\partial T}{\partial y} + i\frac{\partial T}{\partial x}\right), \quad (2.16)$$

assuming that the horizontal temperature gradient is independent of z. This geostrophic wind change can be quite large: for $f = 10^{-4}$ s^{-1}, $\partial T/\partial y = 3 \times 10^{-5}$K m^{-1}, and $z_i = 1000$ m, (2.16) gives $\Delta U_g = 10$ m s^{-1}. According to (2.15), this is balanced (in the simplest case) by a combination of friction (through stress curvature) and Coriolis force (through mean wind shear in the vertical). We would like to know how the mixed layer apportions this balance.

We can attempt to answer this question by beginning from the steady, nonentraining, nonadvecting, barotropic case, where we have from (2.15)

$$0 = 8\frac{\delta\tilde{\tau}_e}{z_i} - if\Delta\tilde{W}_e. \quad (2.17)$$

This relates the equilibrium velocity change across the mixed layer, $\Delta\tilde{W}_e$, to $\delta\tilde{\tau}_e$, the departure stress linearity. Possibly a relation analogous to (2.7) exists for $\Delta\tilde{W}_e$, but to my knowledge it has yet to be developed. If we again use the closure

$$\delta\tilde{\tau} = \delta\tilde{\tau}_e - \frac{K}{z_i}(\Delta\tilde{W} - \Delta\tilde{W}_e), \quad (2.18)$$

then we find the counterpart to (2.13):

$$\frac{\partial}{\partial t}(\Delta\tilde{W} - \Delta\tilde{W}_e) + \frac{8K}{z_i^2}(\Delta\tilde{W} - \Delta\tilde{W}_e) = w_e \frac{\partial\tilde{W}}{\partial z}\bigg|_{h_1} - \Delta\tilde{A} + if(\Delta\tilde{W} - \Delta\tilde{W}_e - \Delta\tilde{W}_g) - \frac{\partial}{\partial t}\Delta\tilde{W}_e. \quad (2.19)$$

Equation (2.19) has a simple solution in the steady, nonentraining, nonadvecting case:

$$\Delta\tilde{W} = \Delta\tilde{W}_e - \frac{i\Delta\tilde{W}_g}{m - i}; \quad m = \frac{8K}{fz_i^2}. \quad (2.20)$$

In component form, this can be written as

$$\Delta U = \Delta U_e + \frac{\Delta U_g}{m^2 + 1} + \left(\frac{m}{m^2 + 1}\right)\Delta V_g, \quad (2.21)$$

$$\Delta V = \Delta V_e - \left(\frac{m}{m^2 + 1}\right)\Delta U_g + \frac{\Delta V_g}{m^2 + 1}. \quad (2.22)$$

Note that as the mixing parameter $m = 8K/(fz_i^2)$ becomes large the turbulence is able to keep the wind shear small compared to the geostrophic wind shear, and the balance required by (2.15) is achieved mainly through stress curvature. Strongly curved stress profiles have been measured in baroclinic situations (Kaimal *et al.*, 1976; Lenschow *et al.*, 1980).

These arguments suggest that "unmixed" mean wind and scalar mixing ratio profiles within the convective PBL are apt to result from strong time changes, differential advection, entrainment, and baroclinicity. Understandably, researchers avoided these complications in the first generation of PBL experiments, in order to concentrate on the simplest cases. However, the subsequent broad decline in field research has left us with an inadequate data base on the structure of the PBL in the presence of these complications. New research techniques (such as turbulence simulation) for studying such flows offer great promise, however.

We conclude that accurate prediction of mean profiles by a PBL model requires a reliable turbulence closure (for the turbulent flux), adequate horizontal resolution (for baroclinity and mean advection), and adequate treatment of the coupling between the PBL and the surface, and between the PBL and the overlying atmosphere (for time changes and entrainment). This has implications for PBL modeling, as we will discuss in Section 3.

We know least about the interfacial layer. To my knowledge no similarity framework has been proposed for it. Its physics seems quite complicated, and involve the structure of the overlying free atmosphere and of the mixed layer below. It can also include clouds, since

in fair weather conditions their base often is near the top of the mixed layer.

What would we like to know about the interfacial layer? A short list would include its thickness; the influence of shear-generated turbulence on its structure; how it determines the entrainment rate; the influence of clouds on its structure; its influence on the mixed layer below.

Our present understanding of these topics has been gained largely through laboratory experiments (e.g., Deardorff, 1979; Deardorff and Willis, 1982; Deardorff and Yoon, 1984). While these studies have given valuable insight, we should not be content to rely completely on them for our applications to the atmosphere. Some questions, for example the apportionment of wind shear (in both speed and direction) among the surface, mixed, and interfacial layers in the entraining, baroclinic, convective PBL, might involve issues not accessible through laboratory experiments.

How can we learn these things? A generation ago we would have thought first about direct measurements through tall towers and/or aircraft. Such direct thrusts can now be prohibitively expensive. Today we tend to think instead in terms of numerical modeling, and a currently popular variety is called "second-order closure." Such models can give answers to our list of questions, but raise an even more difficult question: How reliable are these answers?

The experience with second-order closure models in engineering fluid mechanics is illuminating. The field grew rapidly in the 1970s in response to the growth in computer power. Data bases on turbulent flows did not grow nearly as fast, however, which concerned some workers; Bradshaw (1972), for example, pointed to the "fact gap" between our voluminous predictions of flow structure and our limited measurements of this structure. Some were more outspoken on turbulence modeling; Liepmann (1979), for example, wrote:

> "I am convinced that much of this huge effort will be of passing interest only. Except for rare critical appraisals such as the 1968 Stanford contest for computation of turbulent boundary layers, much of this work is never subjected to any kind of critical or comparative judgment. The only encouraging prospect is that current progress in understanding turbulence will restrict the freedom of such modeling and guide these efforts toward a more reliable discipline."

Efforts to make critical assessments of these turbulence models did continue, however. At the recent Stanford conference, Kline (1981) found the progress toward universal second-order closure models discouraging. He summarized:

> "Given the review above, I have little faith that we will find a single, reasonably fast, accurate turbulence closure model. The evidence suggests, to me at least, that the profitable road for engineering calculations in the near and intermediate future is *systematic exploitation of zonal models tied directly to structure features of the flow*. When we have done that in special cases, we have often succeeded."

Many second-order modelers of the PBL have recognized the need for special closures for convective and stably stratified turbulence; Zeman (1981) has described some of these in detail. In effect, they have been developing zonal models.

Lumley (Kline *et al.*, 1981, p. 767) is more optimistic about the search for universal second-order models. He writes:

> "I believe it makes sense to search for models that cover as large a domain as possible on the basis of better physics; I base this belief on the success that has been experienced in the last decade in extending existing models on a physical basis to new situations. . . . Models . . . are under development that have every appearance of being much more nearly universal. . . . I feel that . . . if we are to extend the existing models, the only hope is by consideration of the physics."

This experience with turbulence modeling, coupled with the rapid growth in computer power, has stimulated strong interest within the fluid mechanics community in turbulence simulation, or three-dimensional, time-dependent turbulent flow calculation (Rogallo and Moin, 1984). "Direct" simulation, which resolves the entire eddy size range, is restricted by computer size to low Reynolds number flows. "Large-eddy" simulation, or LES, resolves only the energy-containing eddies and parameterizes the subgrid-scale eddies.

Deardorff applied LES to channel flow before he used it to study the structure and evolution of the PBL (Deardorff, 1974a,b). His LES studies contributed much to the PBL information explosion I referred to earlier. Moeng (1984) has developed a new LES code with updated numerics. Nonetheless, the technique is not yet widely used as a research tool in boundary-layer meteorology. With the anticipated advances in supercomputers, we can look forward to decreased costs for LES studies of the PBL, making it more attractive to carry out some of our "field programs" on the computer (Wyngaard, 1984b). Realizing this potential will probably require a new generation of interactive graphics software which allows researchers to work in what Zabusky (1984) calls the "heuristic mode." Perhaps before long the computer will begin to close the fact gap that Bradshaw (1972) feels it created!

b. Stable PBL

The effects of stratification, either stable or unstable, are most pronounced for the largest eddies. Since these largest eddies give a turbulent flow its distinguishing characteristics, it is no surprise that the stable and unstable PBLs are completely different. Figure 6 shows an artist's conception of the stable PBL; comparing it with Fig. 2, we note it is shallow, with pronounced mean gradients within it, and has small eddies with superimposed gravity waves.

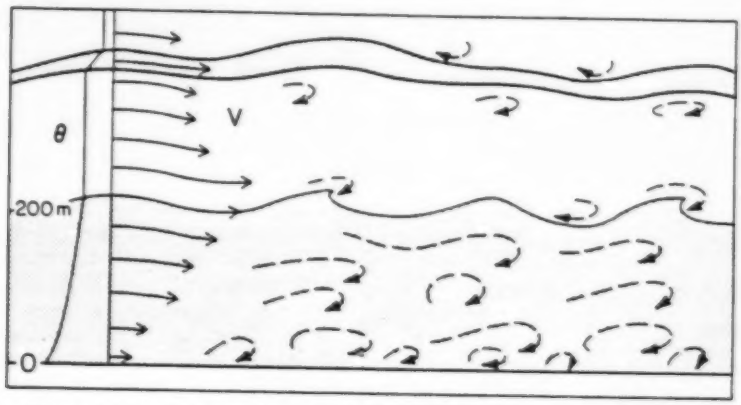

FIG. 6. An artist's representation of the local structure of the nocturnal PBL showing its relatively thin turbulent layer, small eddies, wind jet, and wave motion.

The practice of distinguishing different layers within the stable PBL is less well-established than in the convective case. However, Wetzel (1982) has developed a simple three-layer parameterization which has a surface layer, a turbulent layer, and an accumulation layer which provides the transition to the free atmosphere. This upper layer is nonturbulent but does have a potential temperature gradient; its top is the height to which the cooling extends. The top of the turbulent layer, on the other hand, is often revealed clearly by monostatic acoustic sounder returns; it can be considerably lower than the depth inferred from a temperature profile. Yu (1978) showed that simple diagnostic models (which presumably attempt to predict the depth of the turbulent layer) correlate very poorly with profile observations. Mahrt *et al.* (1982) show that these simple models perform much better when tested with a suitable estimate of the depth of the turbulent layer. André (1983) shows that this depth varies much more from night to night than within particular nights, however, and shows that this can strongly bias the evaluation of depth models.

The near-surface region is the most nearly neutral; the stratification (measured by a Richardson number, say) increases monotonically with height, reaching a critical value at the top of the turbulent layer. Intermittency can become pronounced there, as it does near the edge of a free turbulent flow in the laboratory. Gravity waves, which can interact with and modulate the turbulence (Finnigan and Einaudi, 1981; Caughey, 1982; Fua *et al.*, 1982; Einaudi *et al.*, 1984), are a further and not well-understood complication.

The turbulence in the stable PBL is produced by the mean wind shear; it is destroyed by buoyancy effects and (at a greater rate) by viscous dissipation. As a result, its energetics can be in a delicate and precarious balance, and extremely sensitive to changes in the mean wind profile (whose shear is its energy source) and the mean temperature profile (whose stable lapse rate severely limits its vertical motions). Not surprisingly, then, the similarity statements we can make about the structure of the stable PBL are of a different nature from those for the convective case.

The height h of the stable PBL (I refer here to the height of the turbulent layer, in Wetzel's notation) is determined by the turbulence dynamics, which in turn are determined by the vertical wind and temperature structure; these tend to be inherently time dependent, so that h is also. Nieuwstadt and Tennekes (1981) have derived a rate equation for h, starting from the turbulent kinetic energy balance. They found

$$\frac{dh}{dt} = (h_e - h)/T, \tag{2.23}$$

which indicates that h relaxes toward an equilibrium value h_e with a time scale T. They find that T is a few hours at the beginning of the night, but that later it can easily become of the order of 10 hours; thus, h generally does not reach its equilibrium value. Stull (1983) proposes a different scaling depth for the stable PBL, one based on the time integral of the surface temperature flux, and shows that (2.23) also describes its dynamics.

Just as the PBL height is apt to be time dependent, so are the wind profile, the temperature profile, and the surface energy budget, which provides the surface cooling which usually creates the stable stratification. Thus, the turbulence structure typically evolves with time. Caughey *et al.* (1979) have used scaling arguments to show that it usually should be able to "track" these changes, however, since they typically are slow compared to turbulent time scales.

A simple but apparently effective closure hypothesis for the turbulence in the stable PBL is the following: The integral scale of its three-dimensional, quasi-steady motions is limited by the vertical scale over which ap-

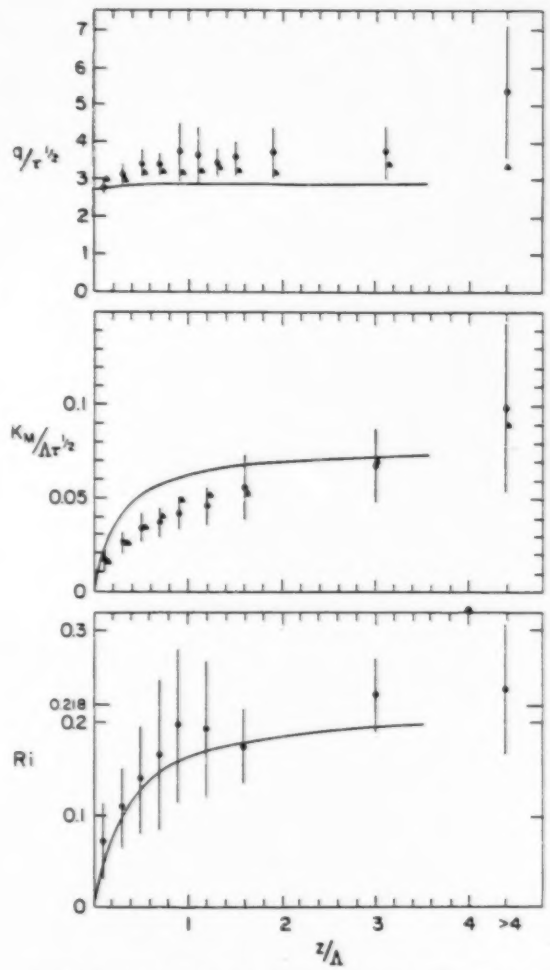

FIG. 7. Some observed statistics from the nocturnal PBL (data points) and theoretical predictions (solid curves) from Nieuwstadt (1984). Solid triangles are high-pass filtered data (cutoff frequency 0.01 Hz); solid circles are unfiltered; vertical bars are $\pm 1\sigma$ for the data which are averaged over stability ranges. Abscissa is z/Λ, where Λ is a local M–O length which arises through use of the closure (2.24). Upper panel: rms turbulent energy, scaled with local friction velocity; middle panel: dimensionless eddy diffusivity K_m; lower panel: Richardson number.

preciable kinetic-to-potential energy conversion occurs. This leads (Brost and Wyngaard, 1978) to a closure expression in the form

$$lN/q = \text{constant}, \tag{2.24}$$

where $q^2/2$ is the turbulent kinetic energy, l is the integral scale and N is the Brunt–Väisälä frequency. This is essentially a constant "turbulent Froude number" hypothesis. In Wyngaard, 1983, it is shown that one can also obtain this closure through Richardson number arguments, as used by Lilly *et al.* (1974), or through scaling with the local Monin–Obukhov length, as used by Delage (1974). This is another example of "zonal modeling" (Kline, 1981) in that it is tailored specifically for stably stratified, shear-driven turbulence.

This is basically the approach followed by Nieuwstadt (1984); his predicted stable PBL structure agrees impressively well with measurements made at Cabauw by his Dutch colleagues, as illustrated in Fig. 7.

Thus, the similarity framework for the stable PBL is a set of equations for structure, rather than descriptions of structure (as in the convective case). Perhaps this is why order in the stable PBL has been so elusive to experimenters. If we also recognize that the stable PBL is apt to respond to very slight slopes, and to the effects of terrain inhomogeneities, then we should expect that the night-to-night and site-to-site differences in stable PBLs should be substantial, as argued by André (1983). If, in addition, we add the consequences of the inevitable time evolution during the night, and of the possibly two-dimensional turbulent motions which could evolve from the three-dimensional turbulence in the presence of the stable stratification (Lilly, 1983), we should perhaps be surprised if the first generation of experimenters had been able to perceive much order in the structure of the stable PBL.

3. Building models

Ideally, today's meteorological and air pollution models would include today's descriptions of PBL physics. In fact, however, typical rural diffusion models, at least, do not (Smith, 1984). Let's consider some factors bearing on the design of a new generation of improved models.

a. Inherent uncertainty

The local structure of the PBL can differ greatly from its average structure, and, hence, from the structure predicted by even a perfect model. This has been recognized in the dispersion community for some time (e.g., Gifford, 1959) but, nonetheless, some early work left the impression that one-hour averages, say, removed most of this randomness. Recent data sets (e.g., the EPRI Kincaid set, Bowne, 1981) show that the scatter in several-hour averages of concentration during convective PBL diffusion experiments is typically so large that one has difficulty differentiating between good and poor models. This was also the case in a recent assessment of rural diffusion models (Smith, 1984). This cannot but inhibit the building of models with better physics, for what are the rewards of building a better model, if not better predictions?

In practice, of course, better models usually do give better predictions, as testing against larger and more complete data sets would show. Currently we can generate these sets most readily in the laboratory (Willis and Deardorff, 1976), but some encouraging results

are now coming from experiments in the convective PBL at the Boulder Atmospheric Observatory (Briggs, personal communication, 1984). Large-eddy simulation has also been used successfully in applications to dispersion (Lamb, 1982). Ultimately, we will be able to use data from these three sources to test and require models not only for mean concentration, but also its inherent uncertainty.

b. *Balance in model building*

Much has been written in recent years about PBL modeling, particularly in review papers (Blackadar, 1979; Zeman, 1981; Wyngaard, 1982). Most of these papers focus on details such as closure approximations, grid structure, and the like, within the broad context of "high-resolution" models having many grid points in the vertical. Such models represent the state-of-the-art treatment of the PBL within, say, a regional meteorological model.

These contemporary high-resolution PBL models have some important limitations, however. They can be quite expensive to run, requiring on the order of 40% of the total computation time in a dynamical mesoscale model, for example. Second, their closures, whether *K*- or second-order, have deficiencies which can be serious in some applications, and it is not clear how to improve them. There are, however, some interesting new possibilities, including integral closures (e.g., Fiedler, 1984). Third, their horizontal mesh is usually much coarser than the vertical; thus, the model's ability to resolve differential advection and baroclinicity, which I argued earlier can lead to vertical structure in the PBL, could be poor. One wonders: Is it worth spending 40% of the computation time on a model component with these inherent limitations? In some applications the answer is clearly no.

This raises the question: What is the proper balance to strike in building a PBL model? How much weight should one give to the surface energy budget, to horizontal resolution, to vertical resolution, to the turbulence closure, to PBL depth, to cloud parameterization, or to the effect of stability on PBL structure? This is a difficult question, and one whose answer depends on the application.

A related issue concerns model architecture. The structural core of today's high-resolution PBL models is typically the discretization in z and the turbulence closure. An alternative is to begin from what Deardorff and Mahrt (1982) call the dh/dt approach; that is, to carry a prognostic equation for PBL depth h, one which describes the evolution of h in response to horizontal advection, turbulent entrainment, large-scale vertical motion, and cloud-scale subsidence. One could then partition into a few sublayers, using, for example, the three-layer representations of Deardorff (Fig. 1) for the convective PBL, and Wetzel (1982) for the stable PBL. In many applications the "local equilibrium" hypothesis then allows one to use integral methods within the individual sublayers. As the name suggests, here one integrates the governing equations over the layer after specifying profile shapes. This eliminates one independent variable, making the approach much faster computationally than a differential (i.e., high-resolution) model.

Integral methods are widely used for engineering boundary-layer calculations, and are also used in meteorology. The well-known "mixed-layer" PBL model is an integral method, but is extreme in that it allows no structure in the vertical. This structure may be particularly important in dispersion applications, and can be included in integral models, as demonstrated by Zeman (1979), for example, for the nocturnal PBL, and by Wyngaard (1984a) for scalar profiles in the convective PBL.

With this integral approach to PBL modeling, one needs parameterizations, or modules, for various distinct aspects of PBL physics. Some of these already exist; for example, Blackadar (1979) describes one for the surface energy balance at night. As another example, a surface-layer module is provided by Monin–Obukhov similarity. Driedonks (1982) presents simple modules for predicting the evolution of daytime PBL depth, and the Nieuwstadt–Tennekes (1981) work provides the nighttime counterpart. Modules which need to be developed include one for the mean wind profile in the convectively mixed layer, and one for the interfacial layer, including the effects of clouds.

In air quality applications one might need modules for dispersion near the source. The broad features of the PBL on which this dispersion depends (e.g., height, stability) are available from the parent PBL model, and some modular descriptions of our current understanding of plume behavior are available (e.g., Lamb, 1982). The inherent uncertainty in concentration depends on concentration fluctuations which are not yet as well understood, but when they are they should also yield to modular descriptions.

In summary, the proper balance to strike in PBL model building is difficult to assess. It is an important issue, however, and one that we should address in order that our next generation of models can make optimum use of the next generation of computers.

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